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Review of the photovoltaic energy program in the state of Minas Gerais, Brazil

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A B S T R A C T

In much of the world, there is increasing demand for electricity to serve rural communities, isolated from the existing grids and typified by low-density electrical consumption. Because these non-urban consumer markets require rather high implementation investments (as well as high operation and maintenance costs), new technological and policy options are required to meet the needs of these markets. These consumers typically use energy in daytime peak hours of electricity, typically for lighting, television, and communication—as well as for a variety of cultural habits such as hot water that impose high demands on the utility's power distribution and generation system. This has been the case in Brazil, making it necessary to identify decentralized generation technologies to meet the potential markets, typically serving rural and poorer areas. The government itself provided the impetus with the passage of the Brazilian "Universalization Law" that mandated supplying electricity access for the entire population by the year 2010. This law allows the use of both the distribution grid and renewable energy off-grid technologies. In response, Brazil's largest state utility, Energetic Company of Minas Gerais (CEMIG) has aggressively implemented the use of decentralized photovoltaic systems to supplement the conventional power grid to satisfy the "universalization" targets. This paper provides a summary of the status and the future prospects of solar photovoltaic Energy in Brasil, within the context of the "universal electricity supply" policy. The focus here is to highlight the successes and the issues experienced to date in the State of Minas Gerais. This includes examining the methods implemented to ensure system reliability for the consumers, as well as the standards established under the Agência Nacional de Energy Elétrica (ANEEL), the national regulator electrical agency that ensures compliance with the federal regulations.

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1. Introduction

The World Bank has conducted a number of careful studies on the impact of rural electrification on poor, and non-electrified communities. They concluded that rural electrification could provide substantial social benefits, such as improved living standards especially for children and women. For example, electrical lighting directly improves the quality of life because it allows children to study in the evening, as well as enhancing their learning conditions during the day in their schools. Electricity allows women to run their households more efficiently, gaining them much needed personal time or even time to earn additional income. Families are provided access to modern communication and information that urban populations now take for granted. Even reliable access to clean water and sanitation becomes the norm, greatly improving the population heath and lowering medical costs [1].

The majority of the world's population that does not have access to electricity is concentrated in the developing countries, and 80% of non-electrified households are located in rural zones. In Brazil, the families who do not have home electricity are at or below the poverty level (having income equivalent to less than two minimum wages (approximately R$ 1000 or 500 US$/month in 2009)). Though this population is found throughout the country, the largest fractions are located in the northern and northeastern regions [2].

Electricity, as already cited, provides improvements in the quality of life. However, it can also stimulate the local economy and the income of "electrified rural communities"—and this is also one of the major drivers for this rural electrification program in Brazil.

The electrification of rural communities have special characteristics, such as: (1) wide spatial dispersal isolated communities, that brings difficulties in terms of logistics, transport, access to communication and economical viability of the projects for the *concessionaries* (defined as utilities that only do electricity distribution); (2) low "human development indicators" with limited public services and low levels of education; (3) non-integration in the formal economy; (4) patterns of low-electricity density and consumption providing little or no return on investments for the concessionaries for such electrification projects [3]. Additionally, the long distances from the urban areas impose high maintenance costs for the electric distribution grid installed in those rural dispersed communities. Due to the peak hour consumption patterns of these remote consumers, the generation and distribution system demands for the utility are higher—which translate into additional costs.

The Brazilian government has committed to supply electricity access for its entire population by the year 2010. Brazil's "Universalization Law" has facilitated the progress in rural electrification. The policy to implement this goal is called "Light for All Program" (or LPT Program), which will bring electricity to about 12 million people, most of whom live in those rural and remote areas. The LPT Program has relied on both grid extension and the use of complementary technologies, mainly from renewable energy resources for the connection of rural communities [4]. Also the regulations imposed by ANEEL (National Electricity Regulator Board) binds concessionaries target areas with specific schedules to realize this electricity access to everybody in Brazil [5]

Some of these "unserved" rural energy users are being supplied by grid extensions. However, larger numbers cannot be "grid connected" because of excessive costs of transmission and distribution. These have been shown to be ideal for decentralized generation technologies, and off-grid electrification (such as that provided by solar photovoltaics) is proving to be not only a more cost-effective, but also a consumer-acceptable solution to supply many of these low-demand, remote consumers.

Of course, the relative competitiveness of these complementary technologies for rural electricity supply depends on the local climatic and geographic conditions, as well as the electricity consumption density (i.e., kWh/km^2/month) of the area being supplied. In general, the average cost for the electricity increases with declining consumption density and increase in the grid extension, actually providing the incentive for use of descentralized generation technologies to meet these markets. In Minas Gerais, the utility (CEMIG) has selected the photovoltaic (PV) technology as the best generation alternative to supplement their electricity delivery based upon the availability of solar resource in the remote areas and the relative cost of the PV system itself. Photovoltaics is central to CEMIG's approach to reach the target established by the LPT Program and Brazil's "Universalization Law" [6].

However, the deployment of this solar technology comes with clear and defined requirements to ensure reliable service and PV system lifetime through testing and certification of the equipment. This is central to the CEMIG approach. This paper provides an overview of the status of solar photovoltaic electricity in Brazil, within the context of the current country policies. The relative metrics and models used for designating the use of PV over grid extension are covered. The procedures and standards implemented to ensure PV system performance and reliability for these remote, rural customers are evaluated in terms of the results to date in the State of Minas Gerais.

2. Context of rural electrification in Brazilian electric sector

2.1. Overview of Brazilian power electricity system

The Brazilian power electric sector is characterized by the existence of a large hydrothermal production dispersed throughout Brazil. The reservoirs are located far from the consumption centers, forcing the system be interconnected by extensive systems of transmission lines managed by the Brazilian National Interconnected Power Electric System (SIN). Only 3.4% of electric generation originates from outside of SIN's authority, ant this is an isolated system is located in the north region of the country (i.e., in the Amazon area) [7].

Brazil's total power electric system has approximately 110 MW of installed capacity. It is composed of: 73% hydroelectric plants, 25% thermal (natural gas, coal, and biomass) and nuclear plants, and 2% renewable energy resources, such as wind, micro-hydro and biomass, supplying energy for 65 millions of consumers [5].

The large dependence on a single source can lead to difficulties. Brazil's 2001 energy crisis was caused by severe drought conditions that crippled the hydro electric generation. This emergency resulted in a more diverse energy portfolio increasing the thermal and distributed generation. The utilities recognized also the importance of including energy efficiency schemes to cut loses and decrease unneeded demands [7]. This also was coincident with the rise of use of renewable energy technologies worldwide, and Brazil

accelerated its investments into wind, biomass, and solar energy became of interest in sustainability of the Brazilian power electrical system for the coming decades. Brazil's need and the world's adaption of these renewable energy sources provided perfect timing for the Brazil energy markets.

In line with the hydropower 'tradition' in Brazil, the government's "Growth Acceleration Program" announced investments in large- and small-scale hydroelectric power plants. Published government plans indicate that there will be an addition of 35 MW from hydropower plants by 2019 [7], indicating that many other large-scale hydro power plants sites will be auctioned for entrepreneurs in this decade, though still subject to licenses. [5].

The studies developed by the Ministry of Mines and Energy (MME) and Brazil's organization for economic cooperation and development (Empresa de Pesquisa Energética or EPE) have directed that the government commits to keeping a large share of renewables in its energy matrix. The Law (n° 10.438 of 2002) created the governmental Alternative Source Incentive Program (PROINFA). This initiative's main objectives are to promote the diversification of electric power generation sources to increase supply security; to prioritize of actions that exploit regional characteristics and potentialities for the reduction of greenhouse gas emission [8]. PROINFA's first phase had a 2003–2008 goal to built 3300 MW of installed capacity, divided equally among wind, biomass, and small hydroelectric power plants. This first phase resulted in 3,299.40 MW that included 1,191.24 MW of small hydro plants provided by 63 small hydro plants, 1,422.92 MW by 54 wind power plants, but only 685.24 MW by 27 biomass-fired power plants [9].

In addition to PROINFA, the federal government since 2005 has conducted annual energy *purchase and sale actions*, including renewable energy resources. Actually, small hydroelectric plants are a growing energy resource, with advantages of cost competitiveness and generally less environmental impacts due to smaller scale of flooded areas. There are 369 operating small hydroelectric power plants in Brazil with an installed capacity of around 3 GW. When all 581 plants under construction and approved are operational, their potential will add up to over 6 GW of installed capacity. There are also 45 installed wind power plants in Brazil with approximately 0.8 GW of installed capacity. There are some distributed biomass plants operating on sugar cane, mainly in the southeastern region. However, the wind power is growing most rapidly in Brasil. When all plants under construction and approved by ANEEL are completed, they will add nearly 3 GW of wind installed capacity [5].

The National Energy Plan for 2030 (PNE) compiled by the governmental Energetic Research Company (EPE) is the first study of its kind to evaluate the Brazilian energy sector in a fully integrated manner. This study is based on a requirement of 216 GW of installed capacity in 2030, which will come from 156 GW from hydroelectric plants, 40 GW from thermal plants (21 GW from natural gas, 6 GW from coal, 7.35 GW from nuclear, 5.5 GW from other resources) and 30.8 GW from renewable resources such as micro-hydro, biomass and wind. Unfortunately, the contribution of solar resource in the country was not considered in this study [10]. The Decanal Energy Plan 2008–2017 indicates plans for the addition of the third Brazilian nuclear power plant by 2015, with no further plans for additional nuclear additions through 2019 [7].

The National Energy Efficiency Program has been very important for the research and development of renewable technology in Brazil. The Law (n° 9.991) of July 2000 established that 1% of *the annual net profit* of the concessionaries and *permissionaries* (defined as private companies that provide rural electrification with the permission of the utility) must be applied in R&D and energy-efficiency projects. These rather substantial investments are divided equally between them. The "50%" R&D part is distributed with "30%" for a national energy research fund, called CT-ENERG, and the Energetic Research Company (EPE), and "20%" must be used by the utility in its *own* R&D projects dedicated to the electric power system. For the generation utilities without electric distribution system, the investments will be only for R&D [5].

Solar thermal water heating has been strongly supported by this program as demand side management technology. The use of hot water during peak times is a considerable problem in the domestic sector due to the common use of "electrically heated" showers. It is a peak hour load, so some concessionaries (most of them in the southeast) are mandating that the electric shower be replaced by less expensive solar thermal collectors. Others solar technologies have been implemented by the National Energy Efficiency Program as R&D projects, such as concentrated solar thermal power (CSP), grid-connected PV, smart windows, building integrated PV and efficient building materials [5].

The investments of the Brazilian electricity sector and the signaling of incentives from government energy-efficiency policies (e.g., feed-in tariffs and renewable portfolio standards) for alternative energy sources make the future of PV solar energy in Brazil very promising. Still, there are still needs for much stronger policies to stimulate and accelerate the solar markets. Currently, the need for rural and off-grid applications are driving the utility investments (through the universalization law). Policy needed to drive the use of solar in the urban, grid-connected environment.

2.2. Rural electrification in Brazil

Electricity is the most widely available public service in Brazil. But the recent study of the Human Development Index (IDH) concluded that the poor areas of Brazil both lack electricity service and possess the poorest quality of life [11]. Electricity by itself is not a vector for development, but it can promote changes in the quality of life for that population.

In the beginning of last decade more than 12 million Brazilians (~2.5 million households mostly in the rural areas) have no access to electricity. Large differences remain between rural and urban populations, among states/regions, and within various income levels, most of them located in the northern and northeastern regions of Brasil [11].

Several public rural electrification programs aimed to electrify rural areas of Brasil were launched over the past two decades. The *Light for the Countryside Program* ("Luz no Campo Programa") was introduced in December 1999, with the main objective of increasing the level of electrification in rural areas. This encompassed 630,000 rural consumers and farms between 2000 and 2003, contributing to the socio-economic development of rural areas in Brazil [9].

Another initiative was the federal government's *PRODEEM Program* (the Energy Development Program for States and Municipalities). It was established by a Presidential decree in December, 1994 [12]. This program aimed to supply rural communities that were not connected to the conventional electricity grid and included autonomous photovoltaics, wind, small hydro, and biomass systems. It was primary government-sponsored electrification program focusing on the electrification of schools, heath centers, and other rural community installations. Photovoltaic solar energy was the *most* used technology, and around 9000 PV systems, approximately 5 MW, were installed between 1996 and 2002. To meet budget constraints, the systems and components were purchased through a centralized method, an "economy of scale" approach in procurement. The implementation was responsibility of the state partner (a concessionary, a state secretary, an NGO, or the municipality) that was also responsible for operation and maintenance of photovoltaic systems.

Since 2002, this program has been undergoing major changes, and where is legally possible it has been incorporated into the *Light for All Program* ("Programa Luz Para Todos") that will be described in the following section.

The National Program for Universal Access "*Light for All Program*" (LPT Program) is a federal government program to implement the 2002 Universalization Law in rural areas, where the people without electricity are located since 100% of urban area is electrified in Brasil [4]. The main objective of the LPT Program is to supply electricity to all rural communities by 2010. The initial deadline was 2008, but the electricity universal access was not achieved, primarily because the number of rural communities without electricity was underestimated during the implementation of Program and due some delays of the target in some Brazilian States. Therefore, the federal government decided to extend the completion to end of 2010 (Decree n° 6442 of April 2008). The scope of the LPT Program defines the following priorities: rural settlements, historical settlements founded by freed slaves (Quilombolas); public schools, heath centers, and public water supplies (wells); projects for collective demand and communities affected by hydroelectric damns; municipalities with low population and a Human Development Index less than 85% [4].

Making use of the successes of several renewable energy projects, this new program sets up three alternatives for electricity supplies to rural areas: (i) extension of the distribution grid, (ii) autonomous off-grid generation using micro-grids, and (iii) individual (stand-alone) electricity supplies. PV systems can be used as stand alone technology in LPT Program [4]. Extension of existing grid was an initial priority, but as the communities became more distant from the grid, the cost of new connections increased substantially. This has been a significant issue or barrier to the concessionaries in meeting the universalization targets.

Previously, rural electrification was controlled and defined at the state level, using the financial resources available from those more local government sources, with the program implementation the responsibility of local concessionaries. Rural consumers would use long-term financing to pay for the connection charge. But, this has changed since in the LPT, and several financing mechanisms for rural electrification have been enacted or extended from previous laws or initiatives. When the LPT Program was initiated billions of dollars were set aside for it.

Sector funds are available as grants from the Energy Development Account CDE (Conta de Desenvovimento Energético) or soft loans as part of the Global Reversion Reserve RGR (Reserva Global de Reversão) [9]. Both funds are available only for agents who are embedded in the legal framework of the electricity sector, including the concessionaries (larger utilities that provide electric distribution services) or permissionaries (smaller electrification companies established in the concession area of a concessionary). States and prefectures funds are combined to provide the universal assistance, and the consumer is assessed if it is in the target area set up by ANEEL for the concessionaries (or permissionaries). Therefore, the consumer does not pay the cost of electrification when the area is included in the target region chosen by the government [4].

The original target of electric service universalization was 12 million people by the year 2010. This target is very difficult to be reached, but, more than 7 million consumers have already been served [11]. This initiative has fundamentally altered the rules for rural electrification because regulation imposed by ANEEL binds target areas and schedules for utilities to bring the universal electricity access into existence.

In Minas Gerais, the *Light for All Program* is implemented mainly by the Energetic Company of Minas Gerais (CEMIG) in partnership with federal and state government, as well the prefectures. In the first 2004–2008 phase of the LPT Program, approximately 200,000 consumer units were serviced by the LPT Program in 774 municipalities within the concession area of CEMIG. It has already constructed an additional 54,000 km of distribution grid, which equals 23% of the entire rural existing CEMIG's distribution network [13].

This program covers new connections through distribution networks, photovoltaic systems for individual and isolated networks with decentralized generation. The alternative will be chosen according to the cost and the technology adaptability [6]. But, CEMIG's market was underestimated (like in the rest of Brazil), and by the end of 2008 it had reached nearly 300,000 potential consumers units. According to the contract signed for the second phase of LPT Program, 55,000 new connections need to be made in 205 municipalities by the end of December 2010 [13].

2.3. Photovoltaic solar energy use in rural electrification in Brazil

Since middle 1980s, PV has been used in Brazil in numerous applications, ranging from cathodic protection and emergency signals to telecommunications, traffic signals, and remote power. Recently, the use of this solar technology in rural electrification has surpassed all the other applications in scope and size. The current 10 MW installed capacity are distributed throughout the country, with more than 50,000 photovoltaic systems already in operation [14].

A first major step toward the use of photovoltaic technology in rural electrification in Brasil was taken under the agreement between DOE/NREL (National Renewable Energy Laboratory – U.S.A.) and Eletrobrás/CEPEL (Brazilian Electric Research Center) in middle 90s. Hundreds of PV systems were installed in several states, with participation of several concessionaries: CEMIG (Minas Gerais), CELPE (Pernanbuco), COELCE (Ceará) and CEAM (Amazonas). These systems are still operational and are the responsibility of local governments and concessionaries. The photovoltaic systems were installed as solar-home systems, schools, heath centers, and churches [14]. The PRODEEM Program (described in the previous section) followed the U.S.-Brasil agreement. PV systems were widely used the electrification of schools, heath centers, and other rural community installations. From 1996 until 2002, more than 7500 PV systems totaling 5 MW were installed throughout Brazil.

Several other initiatives of various sizes and involvements were implemented during this timeframe. The "PRODUZIR Program" organized by CAR (Companhia de Desenvolvimento e Ação Regional da Bahia) was responsible for installing some 15,000 solar home systems (SHS) in rural areas of Bahia [14]. A similar program had been set up by FTV (Fundação Teotônio Vilela) in Alagoas State [14].

ANEEL, which regulates the Brazilian electricity sector, has established partnerships with research centers and universities for monitoring the technical performance of systems in rural and isolated communities. One of these system types is the PV/diesel "genset" hybrid installed in the Araras community (in the Nova Marmore in the State of Rondonia). This system was implemented under a partnership with Federal University of Santa Catarina, LABSOLAR [5].

Currently, only two Brazilian concessionaries officially have PV systems in their "Light for All Program", CEMIG and COELBA (Electric Company of Bahia) [5]. Three areas are critical to the success of the photovoltaic systems in the "Light for All Program". The *first* is concerned with the costs of the univerzalization process, in which PV has been included as a decentralized technology option. As the cost of grid connection projects increase with distance from the existing grid, the concessionaries need to find less-expensive options to decrease the project's costs. This paper presents a methodology to show this correlation and how photovoltaic technology can be economical viable for the concessionaries programs.

The *second* critical point is related to the technical standards of the equipment and training of the users and installers. The certification procedures of photovoltaic equipment in Brazil is under the authority of a group established by the National Institute of Metrology, Standardization and Industrial Quality (INMETRO), under the

Ministry of Development, Industry and Foreign Trade [15]. This certification is the Brazilian Labeling Program [15] for Photovoltaic Systems PBE/SFV and is a partnership among several universities (including GREEN-IPUC from PUCMINAS [16], research institutes, and the Brazilian PV industry. INMETRO set up a group to establish the test procedures adapted to the Brazilian markets, capabilities, and conditions for the PV system components. These procedures are strictly followed to certify hardware (PV modules, BOS equipment, the PV systems as a whole)) and the training procedures for installers [15].

The *third* important area is the regulation of the decentralized, including renewable energy, technologies. The ANEEL Decree n° 083/2004 [17] established the policies for the regulation of the use of individual renewable energy systems. It sets the rules for the utilization of individual decentralized energy options by the concessionaries and permissionaries, and provides very few opportunities for others dealers of rural electrification in Brasil [17]

A photovoltaic system under this resolution is classified as SIGFI, defined as a system of electric generation to supply electricity, using only intermittent energy source, as defined by Article 3, item II, of the ANEEL Decree N° 083/2004 [17]. The SIGFI can only be installed by a concessionary or permissionary in a single consumer unit. According to that decree, systems should be framed in a class of service, classified as SIGFI13, SIGFI30, SIGFI45, SIGFI60, SIGFI80, with energy availability monthly guaranteed of 13 kWh/month, 30 kWh/month, 45 kWh/month, 60 kWh/month and 80 kWh/month, respectively. The energy service must be supplied in *alternate current*, with the levels of voltage and frequency corresponding to the standards of the area where it is installed [17].

The photovoltaic system is specified in terms of its peak power (Wp) of the photovoltaic generator, minimum necessary to meet the rules of ANEEL Decree 083/2004. Therefore, it is necessary to know the particular electricity standards for the regions that will be served by the photovoltaic system to ensure that the energy provide by the system satisfies the service requirement of the regulator board. This resolution also specifies procedures to be used in billing, operational and maintenance services (O&M), rates of discontinuation, among other settings [17].

3. CEMIG's contributions to the implementation of autonomous photovoltaic systems in the brazilian environment

Since 1990, the Energetic Company of Minas Gerais (CEMIG) had been evaluating the use of solar energy in the State of Minas Gerais. This included gathering experiences from previous and ongoing programs in Brasil, documenting the performance, prices, and reliability of PV system components, and establishing the weather and solar resource information for its service area in Brasil. CEMIG paid special attention to applications such as telecommunications, cathodic protection, rural electrification, and grid-connected systems that were pertinent to its own projected distributed electricity interests. CEMIG focused became focused on rural electrification, with the evolution of the regulatory and policy frameworks in the Brazilian government.

The technical and economic viability of solar rural electrification for remote consumers with low density electricity consumption was investigated and initially validated. The main objective was directed to obtaining experience with decentralized generation options as complementary technologies to the conventional grid for rural electrification. To achieve this understanding, several experimental and demonstration PV-facilities were established as proof-of-concept projects. These pilot projects were implemented in close partnership with various national and international entities, such as Brazilian Electricity Research Institute (CEPEL), National Renewable Energy Laboratory (NREL), Federal Republic of German Technical Cooperation Society (GTZ), KfW German Bank, Brazilian Ministry of Mines and Energy, Brazilian states and municipalities, among many others [18].

Between 1990 and 1999, more than 200 PV demonstration projects were implemented. Among these were the following important programs:

- Program of Assistance for Rural Development in Brazil, CEPEL/ELETROBRAS in partnership with the National Renewable Energy Laboratory –NREL [18];
- Rational Use of Energy in Agriculture, coming from CEMIG and technical cooperation with GTZ (Deutsche Gesellchaft fur Technische Zusammernarbeit). [18,19];
- Program for Energy Development of States and Municipalities – PRODEEM, Brazilian Ministry of Mines and Energy (MME) [19,20].

Based on the positive results from these programs, CEMIG created the "Sunlight Program – Rural Pre-electrification using Photovoltaic Systems" in 1999. The main objective was to develop a sustainable model for the use of decentralized generation as a viable rural electrification option [19,20].

The *Sunlight Program* was implemented in partnership with the MME through the PRODEEM, over the period 1999 through 2002. Funding was provided by CEMIG, state and municipal governments and the Ministry of Mines and Energy through the PRODEEM, and German Bank KfW [19].

The Program had three sub-programs. The *first* was the "Solar Home Systems Sub-Program" implemented between 1999 and 2001. Within this, 565 solar home systems were installed in 100 communities covering 30 municipalities, with funding from KfW (German Bank) and CEMIG, in partnership with GTZ. A rigorous socio-economic study was performed as part of this effort. The results demonstrated that the majority of households were willing to pay the tariff (monthly bill). Though they could not afford down payments, they were willing to pay CEMIG's monthly because of the social value and improvement to their lifestyle that resulted [21].

The *second* sub-program was "Rural School and Community Centers Electrification with PV Systems". The aim of this subprogram was to implement TV education and adult evening classes in municipalities that have the State's poorest quality of life. In cooperation among CEMIG and Federal and State Governments, 800 rural schools were electrified by 2004. Under the Sunlight Program, CEMIG *sold energy services* but retained ownership of the system that provide these services—and the utility retained the responsibility for the operation and maintenance, important to ensure reliability electricity delivery from the PV systems to the consumers. Experiences obtained from four previous test models, initially implemented by CEMIG in several rural communities, had shown that the best approach was the most similar to the utility routine. From these studies and analyses, CEMIG determined that it should implement PV technology as close as possible to its "conventional grid routine" (i.e., user training, user-acceptance, financing, reliability and O&M). The main concern was the long-term maintenance in dispersed community in isolated rural areas [18–20,22]. Therefore, consumers paid the similar monthly payment of the grid connected, low-income consumers. CEMIG had a policy to serve these "PV customers" just the same as the grid connected ones. The subsidies for connection and tariffs for operation & maintenance were the same as those for grid-connected situations. The customer was billed quarterly. If the users did not pay two bills consecutively, the PV modules were removed and replaced only after the payments were received [22]. This policy was very effective in maintaining customer service.

Fig. 1. View of CEMIG's PV training center, located at "CEMIG University" in Sete Lagoas, Minas Gerais, Brazil.

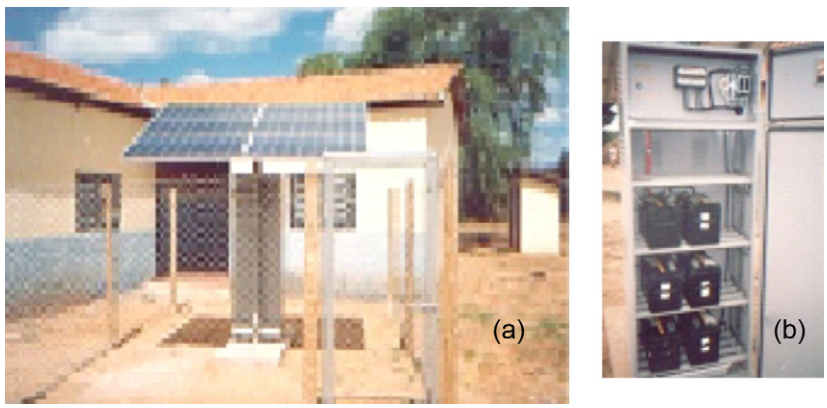

Fig. 2. Typical school PV System – *Light for Knowledge Program*/LPT Program/CEMIG.

The *third* Sunlight sub-program was the "Photovoltaic Solar Energy Training Program", designed to ensure expertise in these newer technologies among CEMIG's team. For this reason the CEMIG *PV Training Center* was set in 1998 as part of the "CEMIG University", an intra-utility educational and training component for its staff. This PV Training Center has produced qualified engineers and technicians for CEMIG and for other Brazilian organizations [19]. Basically the training has involved two major components: (1) technical education on PV from basic principles through system concepts. A major portion is devoted to hands-on training for maintenance using real systems installed at the PV Training Center. The initial target groups were the trainers (teachers or instructors) of CEMIG's PV Training Center and then was expanded to those being assigned to the rural electrification programs (Fig. 1).

When the Light for All Program (LPT Program) was launched in 2004, CEMIG identified a market for installation of 7000 PV systems [6]. Around 2500 photovoltaic systems are now installed in rural areas in homes, schools, and health centers. CEMIG took responsibility for all PV systems installed in the previous programs and upgrading some to ensure that the systems were classified as one type of SIGFI (system of electric generation to supply electricity using only intermittent energy source), following ANEEL Decree n°083/2004 [22,23].

To reach the universalization of rural schools in Minas Gerais, CEMIG and State Educational Secretariart launched a program named "*Light for Knowledge Program*" (Programa Luz no Saber [13]), part of the LPT Program in Minas Gerais. It has benefited more than 1500 rural school in the period 2003 through 2006. Among these, 300 were electrified with PV systems, sum up with 200 rural school benefited by the Sunlight Program and added to "Light for Knowledge Program" [6,13,22,23]. Fig. 2 shows one typical "solar school" of this program.

The program has not yet reached its intended goals. Through 2008, despite the electrification of near 200,000 consumers by the "Light for All Program" in Minas Gerais, only 2000 home were PV-powered in the targeted rural communities [13]; these mainly located in the northern and northeast regions of the State. Priority was given to communities located close to the grid, and the more isolated communities were not reached yet under the program. Fig. 3 shows and example of one rural family that did benefit with a typical solar home system of LPT Program/CEMIG.

The efficiency (or maximum power leading to kWh generated annually) of the photovoltaic systems is very important for the technical and economical viability of these installations. The use of world-standard test procedures and development of methodologies and quality control of the systems were made under the

Fig. 3. Typical solar home system (SIGFI13) – LPT Program/CEMIG.

research project R&D017 CEMIG/ANEEL "Technology Evaluation of Photovoltaic Solar Energy" [24]. The procedures were compiled with national and international standards [24–26]. These procedures were implemented for evaluation of the PV systems used in the *Light for All Program*; that is, samples of all types solar home systems and photovoltaic systems installed in schools and community centers in Minas Gerais [24,26].

These are also in compliance with the National Institute of Metrology, Standardization and Industrial Quality (INMETRO) within the Ministry of Development, Industry and Foreign Trade. This incorporates a energy "labeling" mechanism for the National Energy Conservation Label Program (Programa Brasileiro de Etiquetagem – PBE) [15]. It has the goal of providing the user or consumer information on the energy efficiency of the PV equipment. All the measurements were done on the installations of the solar laboratories of the *Study Group on Energy* – GREEN – IPUC (PUCMINAS) [16,35,36].

4. Methodology and project development

The decision to proceed with a particular electricity delivery system (grid, PV, wind, etc.) was not made by CEMIG without a methodology that considered the major factors that govern the comparative technological competitiveness and risk of a given approach. The relative competitiveness of the different technologies as viable rural electricity supplies depends primarily on the local climatic and geographic conditions—as well as the electricity consumption density (kWh/km^2/month) of the area being served. If a region does not have sufficient solar or wind resource, for example, these technologies cannot serve the customer adequately. As a general rule, the average cost for electricity increases with the declining consumption density which interrelates many parameters, and not just the distance from the grid. These considerations were the basis for the studies developed in this work. This standardized methodology was adopted to ensure quality, system reliability, and equity in system attention and effort, whether a few tens of watts for a communication installation or for a kW-size family residence or school. This section covers a set of these factors that were utilized routinely in the decision making for the CEMIG photovoltaic programs.

4.1. Energy availability monthly guaranteed

The initial step for the calculation of monthly energy availability guaranteed by SIGFI (system of electric generation to supply electricity using only intermittent energy source) and consequently the size of the photovoltaic generator to be used was the identification of global solar radiation of the state municipalities. The State of Minas Gerais has 774 municipalities. The macro region with municipalities located near the capital city, Belo Horizonte, is not considered in this work. Consumers located in this macro region are already electrified with conventional electric distribution grid. Consequently, of the 774 municipalities served by CEMIG, only 400 have been analyzed.

The data of solar radiation of the municipalities, measured at meteorological stations, were obtained from the "Atlas Solarimétrico do Brazil" [27]. This Brasil centric solar database is based on data from more than 500 stations located in Brazil and adjacent areas of neighboring countries. It contains information on daily solar radiation and monthly average. Despite the large area of Minas Gerais, the state has only 79 meteorological stations from the National Institute of Meteorology. For climatological information, the "Normais Climatológicas", maintained by the Ministry of Agriculture [28], was used where possible. Due to the large number of municipalities without information on the incident solar radiation, it was necessary to search for a method to estimate the solar radiation of the municipalities that are not equipped with weather stations.

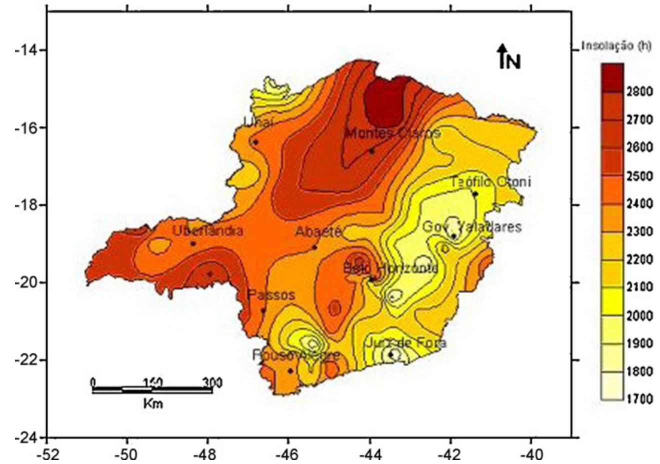

Fig. 4. Solar insolation of Minas Gerais.
Source: [23,25,26].

The resource used to determine the solar radiation in the municipalities without measurement, was the use of "SURFER" software [29] that performs calculations and graphical representation of various geographical variables such as latitude, longitude, temperature, surrounding solar radiation, cloudiness, etc. The method used by this software, to estimate the unknown values, is the method of "Kriging method" which is applied in geostatistics for non stationary situations and concerned with the behavior of so-called regional variables [25]. This science defines the stationary as a homogeneous phenomenon within the area in which it intends to estimate.

Using this method, the solar radiation for each of the 400 municipalities was compiled. The solar resource map generated by the program can be seen in Fig. 4. In this map, we can observe the distribution of solar insolation in the state of Minas Gerais. The west and north regions of Minas Gerais are the ones with largest solar insolation, and these regions require smaller PV generator power and consequently smaller areas of PV panels (less cost), compared an analogous installation in the east part of the state. The solar home system with a smaller PV generator used to power rural households in the *Light for All Program*/CEMIG is the SIGFI13 with energy availability monthly guaranteed of 13 kWh/month. The identification of this value was obtained from the average annual solar radiation, calculated for each municipality of the concession area of CEMIG. From these data, the size of the PV generator (number of panels) is calculated from using norm [24,25].

Fig. 5 presents the solar radiation map that includes the identification of the minimum power of the PV generator for a SIGFI13 system for each municipality. It can be observed that, depending on solar radiation, the state may benefit by the photovoltaic generator SIGFI13 system with three different PV generators sizes – 130 Wp, 140 Wp, and 150 Wp.

In Fig. 5 the red area of the map represents the region of highest solar radiation in the state ($4.97 < Q < 5.26$ kWh/m^2), so the homes located there may be electrified with smallest PV generator, i.e. the lowest power – 130 Wp. The area colored in orange has solar radiation in the range $4.96 < Q < 4.60$ kWh/m^2. Therefore, the minimum power of the PV generator must be 140 Wp. The area with lowest solar radiation, colored in yellow, must be benefited with PV generator at least 150 Wp.

To ensure compliance with ANEEL's audit, as well as for operation and maintenance, CEMIG chose to use solar home system type SIGFI13 with PV generator of 150 Wp in its *Light for All Program*. For

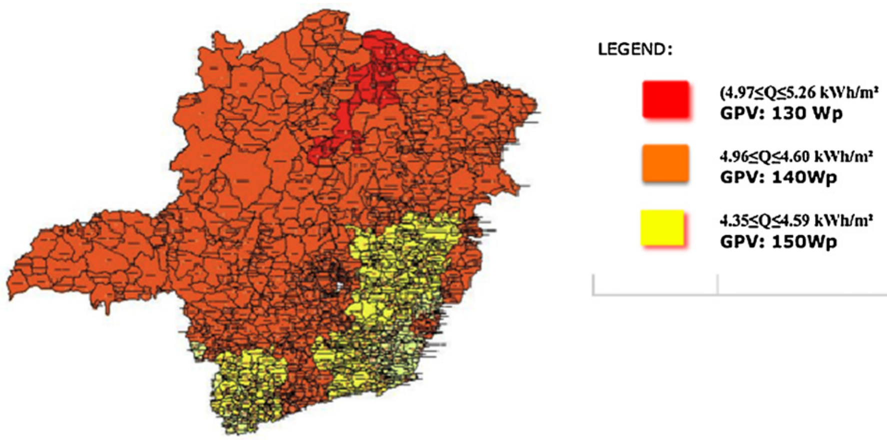

Fig. 5. Mapping of solar radiation and photovoltaic generator size (SIGFI13) per municipality of Minas Gerais State.

the electrification of rural school and communities centers, SIGFI30, SIGFI45, SIGFI80 were used, with monthly energy availability from 30 kWh/month to 80 kWh/month [22,28].

4.2. *Criteria for deployment of photovoltaics technology in the light for All Program/CEMIG*

The criteria for the PV systems to electrify rural households in the *Light for All* Program are based on the energy availability monthly guaranteed (defined in the ANEEL Resolution 083/2004) location of households, the comparison cost of the electrification project per consumer, and the relative benefit between electrical distribution grid and the photovoltaic system. These will be highlighted in this section.

4.2.1. *Location of rural communities*

"Remote" locations have been defined so far as those located in remote areas, isolated and distance from the distribution grid. However, for the considerations used here, these criteria also apply to communities located on island, in areas of environmental protection (which do not allow power lines), or areas of difficult access. If the communities are located on islands, they may be electrified with PV or hybrid systems. But if the communities are located in area of difficult access, they may be electrified with photovoltaic systems or, in some cases, a special designed grid. The type of technology chosen will depend on technical and economic evaluation. The residences and other electrical applications located in areas of environmental protection can be electrified using only photovoltaic systems. And, the decision of the PV system size will depend on the characteristics of the target communities.

4.2.2. *Evaluation of the rural electrification cost*

The criterion of comparison between the technologies to be used in the rural electrification (i.e., electrical grid or PV system) is based in the assumption that the average cost for electricity increases with the declining consumption density and grid expansion. The methodology used to establish correlation between the cost of attendance and distance of consumers to the existing network is based on study done in 1997 by the World Bank [14]. This study sought alternatives for development of renewable energy in rural electrification in Brazil, especially in areas involving Bahia, Ceará, and Minas Gerais [14]. The average cost of the rural electrification project per consumer (*Cgrid*) is obtained from the arithmetic mean of the project cost with the conventional grid and the total number of consumers benefited.

The value of *Cgrid* includes data from the grid length, the dispersion of potential consumers within a cluster, and the existence of other nearby communities that contribute to reducing the cost of electrification because of higher overall consumption density. The cost of the photovoltaic system, defined as *Cpvs* is defined by the cost of equipment, material and installation of the SIGFI13, with PV generator of 150 Wp. A photovoltaic system consists of the generator and BOS components necessary to supply electricity to the consumer unit, following the ANEEL Res. 083/2004 [17]. The cost of the photovoltaic system (Cpvs) is composed of the cost of major equipment, materials and installation. This cost was obtained from a cost survey conducted among different suppliers.

The criterion of comparison between *Cgrid* and *Cpvs* was obtained through analysis of historical data from several years of the implementation of CEMIG's rural electrification programs. The database used consisted of a sample of 6207 projects of rural electrification completed during the years 1999–2002 and 2004–2005. Within this sample, 402 projects were selected, whose communities have 15–25 benefited consumers. The choice of the consumers numbers used in this work was a result of socio-economic research carried out in the *Sunlight Program* that identified clusters with an average of 20 houses in the neighborhood of a rural school [21]. The characteristics of the rural electrification projects with conventional grid were very different, since the number of consumers varies significantly from one project to another. For example, it was found a sample project with 400 consumers benefited and 2976 with only one(1) consumer/project.

The cost function $Y = 435.499 + 2370.711$, in Fig. 6, shows the line that sets the correlation between the average cost of grid project/consumer increases as the grid extension cost increase with the declining consumption density, where Y is the result in real cost of the project per consumer and X is the projection of the grid length in kilometers. Graphically, one can calculate the dispersion is 74.6%. The length of the projected network in the cost graphic in Fig. 6 will determine the competiveness between the photovoltaic system and the grid cost. Therefore, when the project cost is compared with the price of the photovoltaic system, the limit length of the projected network can be obtained.

For a second sample within a given body of data of 6200 projects of the *Light for All Program*, was obtained the equation: $Y = 483.856x + 2375, 097$, with a correlation of 76.4%. This finding confirms the reliability of the first sample used. It is emphasized that this comparison can only be made after the lifting of the actual cost of electrification of the community with the power grid. To be raised the region should be the design of the network to the community, including the topo-graphic survey.

Based on the sample of CEMIG previous rural electrification programs, an analysis of the competitiveness frontier (between grid extension and individual decentralized PV systems) indicates that

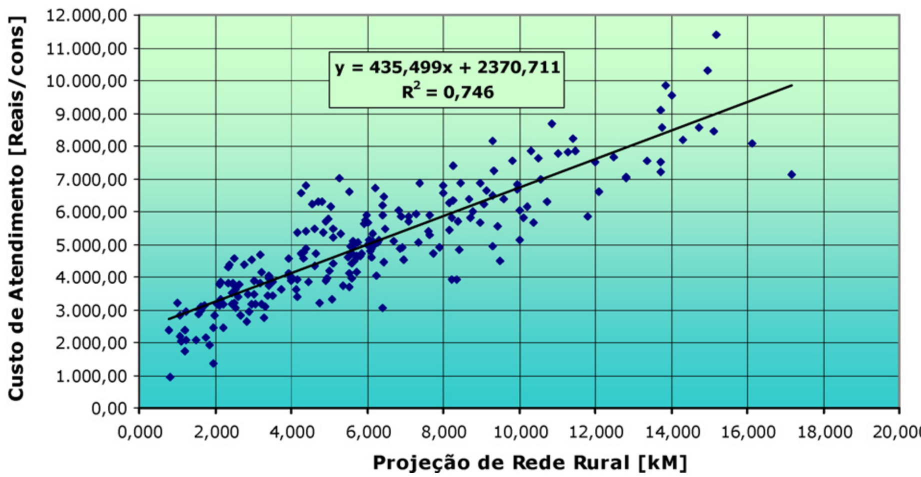

Fig. 6. Correlation between the average cost of grid project/consumer and grid extension cost, for projects with 15–25 users per community.

there is a very good correlation between the average costs per consumer connection and the distance to the existing electric distribution grid. In Fig. 6, the cost of grid extension is shown to be very sensitive to the dispersion of household population—reflecting the declining consumption density and additional maintenance cost.

This analysis led to the cost criterion: when the cost of electrification of the community or isolated consumer with distribution electric grid is at least the double of photovoltaic systems (i.e., Cgrid ≥ 2Cpvs), the photovoltaic technology starts to be competitive and consequently can be the technological choice for electrification of this community.

4.2.3. Characteristics of the user communities

In order to achieve optimal design and sizing of the PV system, it is important to consider the social characteristics of the community's population in addition to technical and economic aspects. Therefore, it is necessary to know the power needs of the Minas Gerais non-electrified, rural communities to avoid social conflicts after those communities electrification.

Jenny et al. [30] and Nieuwenhout et al. [31] reported in their study in communities from several developing countries that energy use behavior was related to both technical and social factors. This necessitated gaining a better understanding how these factors are correlated with multi-user photovoltaic systems. They concluded that systematic and comparative research in rural areas can contribute to optimal sizing of PV systems for rural communities avoiding future social conflicts.

The potential communities of the *Light for All Program* are composed of rural consumers, classified as Small Rural Producer (PPR) and Rural Producer Typical (PRT), settlements, schools, churches, health posts, community centers, and a variety of other buildings. [4].

Electrical Consumers are classified by the Resolution n° 456, set by the National Electrical Regulatory Board (ANEEL), which states that the concessionaries must classify consumers based on the unit loads carried by them [32]. The lower rate applies to the residential consumer unit, characterized as "low income" according to the criteria laid down in specific regulations. Consequently, the consumer is classified as Residential Low Income. This classification also applies to the consumer unit with rural residential purposes under the responsibility of the rural worker, developing agriculture for subsistence [32].

To identify the target communities to benefit from photovoltaic systems in the *Light for All Program* was used the study for evaluation of socio-economic situation of the population benefited with PV systems in the Sunlight Program [21]. The rural worker, identified in this study, is a farmer, using prevailing standards in use in agriculture for a livelihood. The crops are grown with low technology using the family's labor. There is little exchange of surplus production; the crops are used exclusively to feed their own family. The crops more harvested are beans, corn and, okra (annual crops), cassava (not annual crops), banana and vegetables. Some producers benefit from their agricultural production, with emphasis on the production of cassava flour (52% of producers), powder (23% of producers). Data from research shows an average of five (5) residents per home and a predominance of young people in the most productive age group. Overall, 39% of the population surveyed did not attend school.

The producer's income was based on the total monthly family income, including income earned in salary, pension, rent, retirement, donation of land and income of all family members living on the property. The survey indicated that about 30% of producers have family income up to half (1/2) minimum wage per month, 25% income from half (1/2) to one (1) minimum wage income, and 29% between one (1) and two (2) minimum wages. Thus, about 85% of producers have family income up to two (2) minimum wages per month.

The appliances owned by small producers were divided into two categories: domestic goods (radio, TV, refrigerator, recreation, etc.) and assets of multiple use. Of the total population surveyed about 87% did not have any appliances. The average was 0.7 appliances per household. 43% of the households owned a radio, the most common appliance.

The target consumer criterion is that the unit to be benefited with the photovoltaic solar home system (at least SIGFI13) must be classified as Residential Low Income in ANEEL Resolution n° 456, with agriculture for subsistence and income of two (2) minimum wages per month at most, approximately R$ 1000 or 500 US$/month.

4.2.4. Selection criteria

To select the most appropriate technology to electrify the rural communities, CEMIG's engineers and technicians follow a CEMIG internally developed standard (Standard ND 2.11 in ref. 22) which is based upon the criteria discussed in Sections 4.2.1–4.2.3. From this standard, the following must be met for use of PV for rural electrification:

(a) Location: the consumer unit must be located in a remote area, isolated from the distribution electrical grid (or on islands or within areas of environmental protection);

(b) Relative cost: photovoltaics can only be the technology of choice for electrification of the community when the cost of electrification of the community or isolated consumer with distribution electric grid must be at least the double of photovoltaic systems: that is, Cgrid ≥ 2Cpvs;
(c) Consumer restrictions: the consumer unit to for solar home system (at least SIGFI13) must be classified as "low income residential" (ANEEL Resolution n° 456) with agriculturally based with an income of two (2) minimum wages per month maximum;
(d) Exception: for the electrification of rural schools and community centers, only the criteria (a) and (b) have to be satisfied.

4.3. Optimization sizing of photovoltaic systems

The sizing of photovoltaic systems accurately is important to ensure proper operation and reliability, as well as economical feasibility. Proper sizing of stand-alone photovoltaic systems in isolated areas is important and different approaches can be used. The ANEEL Resolution n° 083/2004 requires that the monthly energy availability guaranteed by SIGFI, declared by the concessionaries, for the PV systems inserted into the rural electrification programs can be subject of an audit to evaluate the performance of the system for an assumed load curve of the typical consumer unit [17].

For the assessment of the merits of PV systems TYPE SIGFI13 sizing inserted in the *Light for All Program*/CEMIG, was used a methodology developed within the research project R&D017 CEMIG/ANEEL, "Technology Evaluation of Photovoltaic Solar Energy" [24]. This methodology is a comparative study between deterministic and stochastic sizing of stand-alone photovoltaic system developed by Cabral [33], with the objective of verifying the best method for photovoltaic system modeling. This work also aimed to identify the pertinent sizing parameters for photovoltaic systems, considering that the calculation of the optimal number of photovoltaic generators and batteries based on the Loss of Power Supply Probability (LPSP).

A deterministic simulation model (developed by Sandia National Laboratory [34]) contains no probabilistic components, and when sizing the PV systems one utilizes average seasonal or annual solar radiation values in their analyses, and oscillations in solar radiation and load demands are not incorporated. Generally, deterministic methods consider the capacity of the storage system based on the consecutive number of days in which the demand can be met [33].

Stochastic methods involve the data reduction and estimation of sizing parameters. For stochastic sizing, battery charge and solar radiation of each state of the system are analyzed, as in the model which used the Markov chain, developed by Safie [35]. This model identifies the states in which the load demands are not satisfied. In deterministic sizing, battery performance is not analyzed during operation. Stochastic dimensioning provides a better forecast than the deterministic method for system operation, being more realistic, and, as a consequence, more often economically feasible.

The Loss of Power Supply Probability (LPSP) represents the probability of power generated by both the battery and the photovoltaic generator to be insufficient to attend the demand and when the storage is depleted and its voltage has fallen below the allowed values [35]. A "zero" LSSP means that load will be always supplied and a LSSP value of one indicates that the energy load will never be met by the PV system.

The sizing methodology developed by Cabral [33] under the R&D017 project "Technology Evaluation of Photovoltaic System" proposed stochastic sizing analysis including the Markov chain and beta probability density function [24].

This work portrayed the study of parameters involved in the stochastic sizing of stand-alone used only for the PV systems type SIGFI13. It involved the comparison of the sizing parameters for the stand-alone photovoltaic system, at both the deterministic level (Sandia method) and the stochastic level, developed model by Cabral. A stochastic program was developed for the calculation of photovoltaic generators and batteries necessary for a given load [33,36].

Comparisons were made between the results calculated by stochastic model and the Sandia deterministic method. The obtained results were compared with sizing results for stand – alone systems from the Sandia method (deterministic), in which the stochastic model presented more reliable values.

It was verified that the best method for photovoltaic sizing of SIGFI13 was the stochastic method, since the generated results are more economical and better forecasted [24,25]. It was demonstrated that for a determined Loss of Power Supply Probability, one ANEEL audit can be attended. Both methods showed advantages and disadvantages. Preference is given to the stochastic model due to its ability to better portray the operation of the photovoltaic system type SIGFI13, that is the PV system type most used in *the Light for All Program/CEMIG* [24,25].

4.4. Standards of PV systems of Light for All Program – CEMIG

Based on the technical, environmental, regulatory and safety, the operation and maintenance considerations for the solar home systems within the CEMIG *Light for All Program*, only two types of photovoltaic systems are utilized for electrification of rural households. The *first* is "PV system type 1", classified as SIGFI13 has energy availability of monthly guaranteed 13 KWh/month. The power of the photovoltaic generator for this system type of system is 150 Wp [22]. The *Light for All program* has excluded the use of 130 Wp and 140 Wp PV generators. Fig. 1 shows one of these PV systems installed on a low income household in northern region of Minas Gerais.

The second type is for use on small farms and island settlements. This is classified as "PV System type 2", with photovoltaic generator with power of 300 Wp. However, the monthly energy availability is not guaranteed for this type [22].

For the *Knowledgment Program* inside the LPT Program/CEMIG that electrifies the rural schools, the PV systems are much larger than ones for solar home systems. Their photovoltaic generators are in the range from 400 Wp to 2500 Wp, depending on the area and type of needs of schools (classified as SIGFI30, SIGFI45, SIGFI60, SIGFI80), with energy availability monthly guaranteed of 30 kWh/month, 45 kWh/month, 60 kWh/month and 80 kWh/month, respectively. In most schools the usual loads are lamps, television and VCRs, satellite dishes and sound systems. In some schools, called "nucleus", the systems were designed to provide computer learning laboratories. The photovoltaic systems designed these schools have higher energy availability then the SIGFI80 [22]. Fig. 2 shows one of these rural schools with the installed PV system.

5. Conclusions

The "Universalization Law" mandates that all Brazilians will have access to electricity in the near future. The *Light for All Program* is the implementation program but due to the brazilian rural communities characteristics, it was identified the need to use complementary technologies to grid connections. Actually, autonomous photovoltaic system is the main decentralized generation used in the LPT Program. The alternative has been chosen according to the cost and the technology adaptability. Also providing a social benefit to the users, contributing significantly to quality-of-life improvement.

Consumers need well designed, properly assembled, correctly installed PV systems. They also require the assurance that their systems will be properly repaired when they fail. Consequently, should be available an appropriate maintenance scheme. All these aspects has been focused in CEMIG PV's sustainability model of the PV systems installed in the Light for All Program – CEMIG.

CEMIG's experience with photovoltaic systems has demonstrated both technology reliability and electrification cost effectiveness electrification of remote rural communities in Minas Gerais State. The primary objective is to facilitate the access of lower-income people to education, lighting and communication. The model described in this paper has been demonstrated that PV systems are an effective complement to extension of grid-based power, which is often too costly for sparsely settled and remote regions. To ensure the sustainability of photovoltaic technology, the systems must be integrated into all operational CEMIG's routines to ensure consumer satisfaction.

This study provides a model to implement the photovoltaic technology as a complementary technology to the grid extension to electrify the rural community, with sound criteria for selection the best option as well the development of a comparison model between deterministic and stocastic sizing, to test procedure developments to assure the PV system performance when installed in the LPT Program run by CEMIG in the state of Minas Gerais, Brasil, with the standards to attend the conditions set by ANEEL regulatory audit programs.

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